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14. ABSTRACT

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Silicon Plasmonic Waveguides for the Infrared and Terahertz Regions

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Abstract: Silicon-based plasmonic waveguides are proposed and studied theoretically. A silicon core, silicide underlay, and metal overlay yield propagation losses estimated to be less than 15 cm^{-1} over the 50 μm to 1000 μm wavelength range.

OCIS codes: (240.6680) Surface plasmons; (250.5403) Plasmonics; (310.2790) Guided waves; (160.3918) Metamaterials; (160.3130) Integrated optics materials.

1. Introduction and Background

Although plasmon waveguides have been proposed for optoelectronic applications, acceptance has been hampered by the difficulty of simultaneously achieving tight confinement and low loss. Promising solutions proposed include the insulator-Metal-insulator, (iMi), and the Metal-insulator-Metal, (MiM) [1] waveguide geometries. In particular, the MiM structure is used to improved field confinement in the sub-wavelength cavity geometries of quantum cascade lasers, and the asymmetric "long range surface plasmon" (LRSP) mode of the iMi waveguide achieves relatively low loss with relatively tight confinement [2,3]. Beyond waveguides, both active and passive plasmonic elements enhance emission and detection in III-V compounds, and more recently they have been proposed for group IV photonic integrated circuits [4]. The latter consideration motivates the present paper, which investigates plasmon waveguides for CMOS compatible metal silicides, such as Pd_2Si, NiSi, $PtSi_2$, WSi_2 and $CoSi_2$.

Our recent study of simple Pd_2Si tracks on Si in air [5] suggested that, compared with noble metals, silicides offer plasmon waveguide solutions at ~twice lower frequencies. This observation was based on *ad hoc* criteria for acceptable loss at high frequency and confinement at low frequency. Shifts to infrared frequencies, and the use of silicides, have a number of applications and advantages. Lower plasmon frequencies are more easily generated in two-dimensional structures such as FETs, impacting the field of active plasmonics [6]. Our calculations based on new permittivity data for silicides [7] show that efficiency of plasmon excitation in them by electron beams, e.g by nano-scale field emitters, remains high farther into the IR than for noble metals. We also find experimentally that optical generation of IR surface plasmons at gratings is significantly more efficient for silicides than for noble metals, an effect understood theoretically as resulting from higher surface impedance [8].

This work extends upon reference 5 by considering the case when the dielectric is Si, rather than air, since the high index improves confinement by nearly 4x. In addition, results for double-sided MiM waveguides are presented, where the confinement is fixed by the separation between conductors. The motivation is two-fold: a desire to utilize CMOS compatible processes and an emphasis on IR to enable Si-based plasmonic electronic integrated circuits (PEIC's) with electronic plasmon generators and detectors. Our results indicate that the Si/Pd_2Si waveguides of this work have acceptably low loss and sub-wavelength confinement in the 50 μm to 1000 μm free-space wavelength range (0.3 to 6.0 THz).

2. Experiment and Discussion

Figure 1(a) and 1(b) present metal insulator (Mi) and MIM plasmon waveguide respectively. In each, the dielectric at the interface where the plasmon propagates is Si rather than air, and the bottom conductor is Pd_2Si. For the Mi structures, the *1/e* propagation length, $\mathcal{L}$, along the Z direction, and the *1/e* penetration in the Y

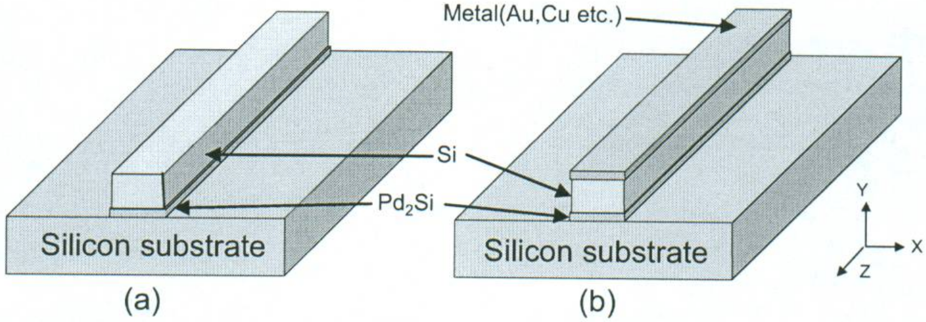

Figure 1: (a) Mi plasmon waveguide of this work formed from Pd_2Si/Si and an MiM Si core plasmon waveguide bounded by either Pd_2Si or a noble metal

direction, L_D , or L_C , calculated from the permittivity [7], are plotted in Figure 2. Subscripts D and C refer to the dielectric (here Si) and the conductor (Au or Pd_2Si). Our *ad hoc* criteria are that the mode should be confined vertically to less than ~3x the free-space wavelength λ and the propagation distance $\mathcal{L}$ should be at least 10x the SPP wavelength. Thus, we find that the Mi waveguide formed at the interface between Si and Pd_2Si, is useable from 12 μm out to 200 μm wavelength. At this long-wavelength limit, the propagation loss is found to be 0.6 cm^{-1}, or ~3 dB/cm.

For the MiM waveguide, the loss can be calculated from [9] $\alpha_{pl} = 2\pi n_d^3\varepsilon''/[\lambda\varepsilon'^{1/2}(n_d^2 + \varepsilon')^{3/2}]$ where ε' and ε'' are the real and imaginary components of the conductor permittivity respectively and n_d is the dielectric refractive index (3.41 for Si). Figure 3 plots MiM waveguide loss for the three waveguide geometries, Au/Si/Au Pd_2Si/Si/Au and Pd_2Si/Si/Au. The double-gold MiM structure has the lowest loss while the loss of the double-Pd_2Si MiM is about 42x higher. Processing considerations favor a MiM structure with a buried silicide followed by deposition of a top CMOS metal to form the Pd_2Si/Si/Au geometry. This structure is seen to have a loss value that falls between the other two extremes. We note that the total propagation loss also must include the intrinsic material loss α_{im} due to phonons and free carriers. Using, $\alpha_{im} = 4\pi\kappa/\lambda$, with κ the extinction coefficient, we have determined α_{im} as a function of λ for intrinsic crystalline silicon. Taking the overall loss in Figure 3 to be $\alpha_{total} = \alpha_{im} + 0.5\ \alpha_{pl}$ (one silicide) + 0.5 α_{pl} (one gold), we find $\alpha_{total} < 15$ cm^{-1} over the 50 μm to 1000 μm wavelength range (0.3 to 6 THz).

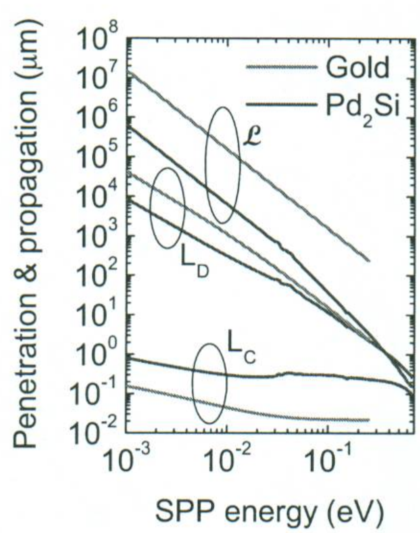

Figure 2: 1/e propagation length ($\mathcal{L}$) and 1/e penetration depth (L) for Si/Au and Si/Pd_2Si Plasmon waveguide

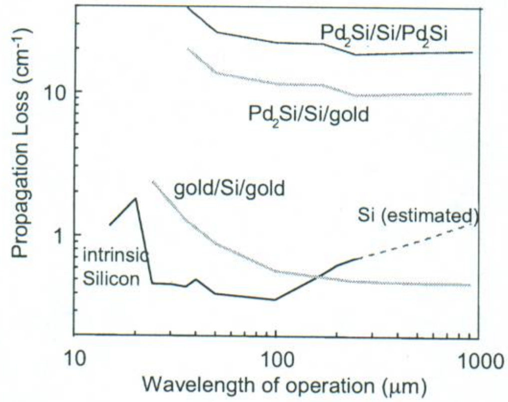

Figure 3: Loss components α_{im} and α_{pl} of the total propagation loss of the MiM silicon-core plasmon waveguide in the far infrared and THz

4. Conclusions

We note a fundamental difference between Mi and MiM type wave guides. The propagation losses of the Mi waveguides continuously decrease as the frequency decreases, because the mode expands more and more into the low loss dielectric. However, this loss of confinement also limits the practical interest in this type of waveguide to wavelengths shorter than (our criterion) $\lambda = L_D/3$, which for Pd_2Si turns out to be 200 μm. In contrast, for the MiM waveguide geometry, the loss tends with decreasing frequency to a constant (Fig. 3), as seen directly from the expression for α_{pl}, where $\varepsilon' \rightarrow$ constant and ε'' goes as $1/\omega$ at low frequencies, while confinement is fixed by the height of the device. However, this constant limiting loss value for the MiM geometry is more than an order of magnitude greater than for the Mi structure.

To conclude, modeling results have been obtained for Si-based CMOS-compatible silicon plasmonic channel waveguides (both MiM and Mi geometries) that operate in the far infrared and THz regions. The overall propagation loss of the Pd_2Si/Si/Au MiM waveguide is estimated to be less than 15 cm^{-1} (or 6.5 dB/mm) over the 50 μm to 1000 μm wavelength range. The Si/Pd_2Si Mi structure has a 4.5 μm to 200 μm practical range. We infer that group IV heterostructures like the Ge/SiGeSn MQW quantum cascade can be used for the dielectric core. We also believe that the strip-like group-IV dielectric can be shaped via photolithography and used to construct integrated and practical waveguide bends, splitters, combiners, couplers and active modulators on a silicon chip.

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